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Enhanced zoogeomorphological processes in North Africa in the human-impacted landscapes of the Anthropocene

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ABSTRACT

New zoogeomorphological features discovered in dryland landscapes of Northern Africa reflect human-animal agency since prehistory, and attest to complex, networked activities over great distances. We discuss the role of zoogeomorphology in shaping Earth's surface since the beginning of the Anthropocene, the timeframe when natural processes shifted and landscape evolution became more human-dominated. We focus on contexts in arid and semiarid lands of Northern Africa, which are metastable, sensitive ecosystems that are prone to modifications triggered by climatic and anthropogenically forced factors. Studying the geoarchaeological record in context of landscape impact and animal procurement by people throughout Antiquity is important for reconstructing domestication and husbandry of cattle, sheep, and goats in this region. Among the features we recognize in association with transhumance, pastoralism, and herding are trails, trackways, footholds, animal daybeds, stables, animal dwellings, rockshelters, game blinds, and monuments, to name a few. Related activities with landscape-scale impacts include herding, transport, corralling and browsing of cattle (*Bos* sp.), goats, and sheep (ovicaprines) as well as pasturage activities like cropping, fire-setting, and manuring. These activities were disturbances that affected surface processes like erosion and dust mobilization, as well as reduced vegetation and ecosystems productivity. In dryland Africa, and especially in the Sahara, intensive herding led to the alteration of the pristine aspects of bare rock surfaces and of the stone desert pavement (i.e., the *hamada*); many regions preserved evidence of middle-late Holocene animal daybeds, trampled areas, and barren tracks and trails. We suggest that human and herd animal activities affected geomorphic surfaces that affected slope stability, intensified erosion and dust mobilization, and enhanced dust export from the African continent offshore. We reinterpret the increased dust emission from North Africa during the mid-Holocene at the end of the African Humid Period, as has been interpreted from ocean cores; aridification of the *Green Sahara* followed the insolation-forced monsoonal maximum, and was exacerbated by human-animal activities across the Sahara and the Sahel. We argue that the spread of human activities and intensive husbandry of cattle, and caprines (goat and sheep) in this region significantly influenced the geomorphic stability, ecosystem and landscape sustainability in a comparable manner of overuse observed in present-day arid and marginal environments, where pastoral overgrazing pressure increases erosion processes and enhances dust mobilization. We suggest that human-animal activities have amplified dust generation from the North African continental interior since ~7 ka BP. This evidence of prehistoric human impacts on surface processes in North Africa supports arguments for an early beginning of the Anthropocene.

1. Introduction

Since Prehistory, humans have actively modified landforms and affected ecological processes. Such agency is throughout Antiquity in contexts where humans have sculpted, mined, and transformed landscapes, as detailed by Butzer (1982) in his book *Archaeology as Human Ecology*. Human influence on geomorphological processes has been characterized in a variety of ways (Price et al., 2011): enhancement of slow ongoing natural surface processes; establishing new geomorphological processes (e.g., excavation removal); changing the physical environment (lithosphere, hydrosphere, atmosphere), and affecting biomes (communities of vegetation and animals). Recognizing the significant long-term and increasing role of human agency in Earth's ecosystems has changed the way geoscientists interpret landscapes (Zanchetta et al., 2013); humans have actively influenced environmental and climatic processes during the timeframe during which they have become dominant on Earth, the principal rationale for defining the Anthropocene geologic epoch (Crutzen, 2002).

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The formal designation of Anthropocene within the geological timescale remains highly debated, both as a concept itself and in terms of its chronostratigraphic inception (e.g., see: Lewis and Maslin, 2015 and references therein). Moreover, the recently approved subdivision of the Holocene epoch into three stages, the Greenlandian, Northgrippian, and Meghalayan, (International Commission on Stratigraphy, 2018) implicitly constrains a very recent definition of the Anthropocene epoch. This decision has fueled a robust debate among scholars, because these divisions are not robustly supported by geological data (see: Lewis and Maslin, 2018; Maslin and Lewis, 2018). According to some scholars, the beginning of the Anthropocene corresponds with the Industrial Revolution, and radionuclide fallout has been proposed as a reference datum to formally define the GSSP (Global Stratigraphic Section and Point) to designate the Anthropocene epoch (Waters et al., 2014; Zalasiewicz et al., 2017).

This is in accordance with the recent definition of the duration of the Meghalayan stage, but alternate suggestions place the start of the Anthropocene earlier, at the formation of anthropogenic soils around 2000 years ago (Certini and Scalenghe, 2011), or even earlier to the onset of large-scale soil management practice and intensive agriculture in the Old World (Cremaschi, 2014). Some scholars argue that humans became dominant in prehistory, during the Neolithic Revolution (Ruddiman, 2003; Ruddiman et al., 2011; Erlandson, 2013; Certini and Scalenghe, 2015), when first farmers and/or herders started actively to modify and directly control the landscape they settled. These human-animal activities increased contributions of greenhouse gases (i.e., GHGs) carbon dioxide, and methane to Earth's atmosphere, and affected global climate change (Ruddiman and Thomson, 2001; Ruddiman and Ellis, 2009). The extra GHGs are the consequences of growing crops, slash and burn practice, animal herding, and extensive rice cultivation. Interestingly, the concept of a Palaeoanthropocene was introduced (Foley et al., 2013), based on various hypotheses about even earlier human fingerprints on climate change and landscape modification.

Besides debates about the formal subdivisions of the Holocene and the placement of the beginning of the Anthropocene, research on the human impact on the landscape can be explored from the perspective of zoogeomorphology (Crutzen and Stoermer, 2000; Butler, 2018). Zoogeomorphology is a subfield of geomorphology and biogeography that focuses on the study of the geomorphic effects of wild and domestic animals on the landscape (Butler, 1995). Various zoogeomorphic impacts characterize various starting dates proposed for the Anthropocene, reflecting the agency of humans and animal populations as modifiers of landscapes and environmental systems (Butler, 2018). Moreover, Butler et al. (2018) described how the zoogeomorphic impacts are dependent on the resilience of each landscape unit. The most sensitive landscape units are metastable, and generally respond rapidly to any hydroclimate- or human-induced change in surface processes (Butler, 2018). As such, dryland landscapes are quite susceptible to change, and they may be among the least resilient; for example, arid and semi-arid landscapes may experience greater zoogeomorphic impacts when fauna are present, and fewer impacts when harsh conditions (e.g., persistent droughts or hyperaridity) or fewer resources (e.g., water, food sources) preclude the presence of animals.

Some view deserts as very stationary, unchanging geomorphic systems; but we argue that arid and semi-arid regions in North Africa are sensitive and responsive to hydroclimate changes (e.g., Claussen et al., 1999; Lézine et al., 2011; Armitage et al., 2015; Henry et al., 2017). Even small changes in precipitation (e.g., rainfall delivery, amount, seasonality, duration, intensity, storm frequency) can affect surface water storage. Even subtle enhancements of soil moisture storage can trigger plant growth, especially in xeric regions, thus promoting surface stability and inhibiting local dust production (e.g., Ginoux et al., 2004; Jury, 2018). During the Anthropocene, humans also actively modified dryland landscapes in this region at different scales; for instance, the introduction of domesticated animals has played a prominent role in shaping the recent evolution of selected desert landscape units, and has affected erosional sediment yield and dust emission.

Here, we present an integrated geoarchaeological, ecological and cultural perspective regarding the zoogeomorphological processes active in arid and semiarid lands of North Africa during the Anthropocene. In North Africa, geoarchaeological evidence suggests that the role of human agency has escalated since the Neolithic *revolution* around the eighth millennium BP. Our discovery of various features across the landscape enables us to link pastoral activities of prehistoric humans and animals with subsequent effects on the landscape. Documenting new feature contexts for cultural activity and geomorphic processes, we discuss North African dryland environments in the context of important cultural transformations, including the domestication of animals, transhumance, pastoral practices (Fig. 1), and extensive herding (Marshall and Hildebrand, 2002; Badenhorst et al., 2008; di Lernia, 2013a; Mitchell, 2018; Brass, 2018). We explain how these cultural and animal activities are embedded in the regional archaeological record as features and monuments (e.g., di Lernia, 2013a), as well as in rock art (Gallinaro, 2013) (Fig. 2). In this paper, we: (i) relate new insights about how the sensitive landscape of the Sahara and adjoining regions preserves zoogeomorphic traces of activities from Antiquity; (ii) suggest that these zoogeomorphic features themselves comprise specific and important cultural and paleoenvironmental archives; and (iii) reinterpret human-animal impacts on the environment in context of the Holocene African Humid Period (AHP), a timeframe popularized as *Green Sahara*.

2. Regional climate, palaeoclimate, and environmental context

The present-day North African climate (Nicholson, 2011) includes three distinct regions: (i) the temperate, circum-Mediterranean region with dry summer and winter precipitation driven by westerly cyclonic disturbances; (ii) the Sahara, which is a subtropical desert, dominated by subtropical anticyclones throughout the year; and (iii) the Sahel. The Sahel region also lies within the tropical latitudes and is influenced by subtropical highs and the migration of the Intertropical Convergence Zone (ITCZ), which fluctuates seasonally as a function of solar insolation (Nicholson, 2011). As such, Sahelian Africa has a monsoonal climate with summer rains and winter drought (Gasse, 2000). The continental North African climate is further modulated by the El Niño Southern Oscillation (ENSO), which varies at a sub-millennial timescale (Wolff et al., 2011; Marriner et al., 2012).

Because of precessional insolation forcing predicted by Milankovitch orbital cycles, the climate and environment of North Africa was markedly different during the Holocene; compared to today, conditions were less arid prior to 5 ka BP, and then became more arid, with the onset of present-day conditions over the past two millennia (e.g., Gasse, 2000; Nicoll, 2001, 2004; Lézine, 2009a; Gatto and Zerboni, 2015). For context, the specific relevant Holocene climate changes of North Africa are summarized in the following section.

In general terms, the so-called AHP started soon after the end of the Last Glacial Maximum, with expansion of the Sahel zone at the beginning of the Holocene (Gasse, 2000). The insolation-forced strengthening of the monsoon increased the advection of moisture from the Atlantic and Indian Oceans considerably enhanced rainfall in the Sahara and across the continental interior region in comparison to today. During the early and middle Holocene, this caused enhanced surface water storage, the filling of lake basins and the reactivation of several drainage networks in the Sahara, as well as the northward expansion of Sahelian vegetation, which colonized specific areas. From the geomorphological point of view, the *Green Sahara* phase was characterized by increased hydrographic processes at springs, lakes, and drainage networks, as well as enhanced soil-forming processes (e.g., Gasse, 2000; Nicoll, 2001, 2004; Cremaschi et al., 2010; Zerboni et al., 2011; Gatto and Zerboni, 2015).

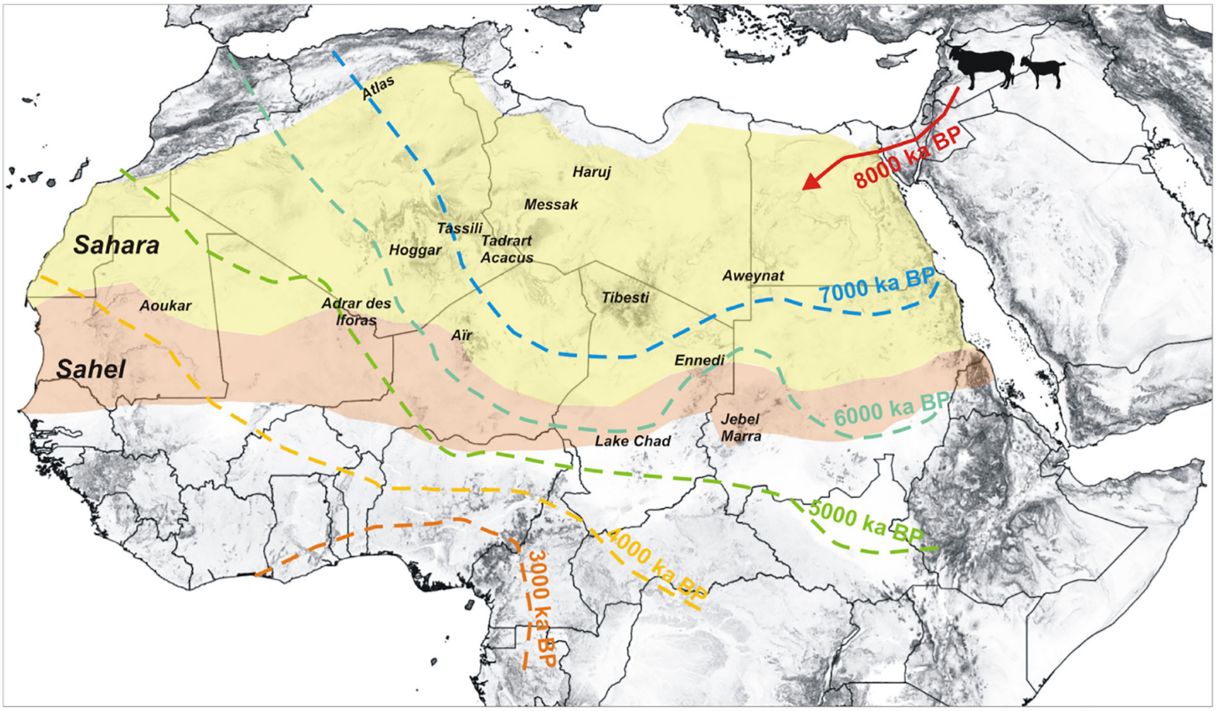

Fig. 1. Map of North Africa indicating the Sahara and Sahel regions, and the time and steps of the introduction of cattle and goat in the prehistory. (After Wright, 2017).

The AHP was interrupted by several dry episodes or droughts, but these are difficult to reconstruct in regards to their length and severity. Drought onset was a function of various factors, including temperature and precipitation frequency, as well as the magnitude of rainfall events. Some of the Holocene droughts are thought to be short-lived in duration, and their effects were probably nonuniform and spatially discontinuous; other dry phases were longer in duration, with more persistent dry conditions, greater magnitude water deficits, and highly regional in scale. The most significant dry interval is likely linked to the 8.2 ka BP worldwide cooling event (e.g., Thomas et al., 2007), as confirmed by several palaeohydrological records in North Africa (Cremaschi et al., 2010, 2014; Hoelzmann et al., 2010).

The inception and duration of the AHP wet phase is well known, but agreement is less about when and how rapidly or slowly the humid period ended because of a lack of well-dated and continuous continental stratigraphic sequences. Researchers interpreting marine sediment cores inferred an abrupt end to the AHP around 5 ka BP (e.g., deMenocal et al., 2000; McGee et al., 2013; Tierney et al., 2017), but inland sites such as Lake Yoa and other terrestrial archives in the central Sahara show a diachronous, geomorphologically controlled response from north to south, and from east to west (e.g., Kröpelin et al., 2008; Cremaschi and Zerboni, 2009; Lézine, 2009a; Francus et al., 2013; Shanahan et al., 2015). Other records indicate that the local geomorphic response to climate change was highly variable across the region (Nicoll, 2004). For instance, in the part of the central Sahara that lies

Fig. 2. A rock art gallery with cattle in the southern Tadrart Acacus massif (Libya).

within the Libyan border, water resources located in the montane areas persisted through to mid-Holocene aridification as compared to surficial aquifers located between dune fields (Cremaschi and Zerboni, 2009, 2011).

Aridification-forced changes in surface processes and vegetation triggered mobilization of dust from dry siliciclastic sediment sources on land, and transportation of dust from the continent to ocean basins, the records of which are interpreted from offshore core records in West Africa and the Mediterranean. The early Holocene and the AHP wet period has a generally low siliciclastic sediment flux between ~12.3 and 5.5 ka BP (Cole et al., 2009). Terrigenous input had a short-term intensification at around 11.9 ka BP and an abrupt increase at the end of the AHP humid phase, at ca. 5 ka BP (deMenocal et al., 2000; Cole et al., 2009; McGee et al., 2013). Chemical and $^{87}Sr/^{86}Sr$ isotopic archives preserved at ODP site 658 offshore of West Africa suggest that for the first part of the Holocene, dust had a sediment supply derived from palaeolake basins that were prevalent across the North African landscape (Cole et al., 2009). However, inland records for dust emission (Lake Sidi Ali in Morocco) suggest a more complicated scenario, with the early and middle Holocene humid period marked by two main dusty phases, and an increase in the frequency of dust events after 5 ka BP (Zielhofer et al., 2017).

3. Humans and herding in North Africa

The introduction of herding within the cultural landscape dominated by hunter-gatherer groups was complex in North Africa. Ameliorated environmental conditions across the region facilitated the practice of transhumance, where the *Green Sahara* supported occasional grasses that provided animals with forage. Moreover, animal husbandry and transhumance left traces on the landscapes of North African deserts. If we consider the arid and semiarid regions, significant cultural revolutions include the introduction of cattle (*Bos* sp.) and domestic ovicaprine (goat and sheep) (Fig. 1) during the early-middle Holocene (di Lernia, 2013a), the domestication of donkeys (*Equus* sp., *africanus asinus*) in Egypt in the fourth millennium BCE (Sutton, 1985; Blench, 2000; Rossel et al., 2008; Mitchell, 2018), and the later introduction of dromedaries (*Camelus dromedarius*) to support the caravan routes across Egypt and North Africa around the first/second millennium BCE (Rowley-Conwey, 1988; Knoll and Burger, 2012; Almathen et al., 2016).

The diffusion of herding has been described as intermittent, resulting in a spotty distribution of small pastoral groups across the region (Barham and Mitchell, 2008; di Lernia, 2013a). Notwithstanding, cattle husbandry effloresced across the whole of North Africa. According to some hypotheses (see di Lernia, 2013a, for details), the arid phase, dated around 8 ka BP, triggered the mobility of herders and rapid colonization of the suitable ecological niches of the region. After the initial phase of colonization, cattle and ovicaprine were evident over much of North Africa by 6 ka BP (Hassan, 2002; di Lernia, 2013a), involving several cultural implications (e.g., Applegate et al., 2001; Tauveron et al., 2009; di Lernia et al., 2013). In the Sahara, the herding apogee at this time may have been influenced by the increased human population density (Manning and Timpson, 2014). Numerous archaeological indicators (i.e., rock art, funerary practices, pottery decoration, settlements systems) and statistical analysis of radiocarbon dates suggest that people with cattle and ovicaprines (goat and sheep) were dispersed over the Sahara and the Sahel by around 5 ka BP (di Lernia, 2013a). The dispersal of cattle herding south of the Sahara, possibly took longer than the ovicaprines dispersal due to ecological reasons of adaptation to Sahelian environmental conditions (Gifford-Gonzales, 2000).

The dromedary was domesticated from wild ancestors in the Arabian Peninsula (Almathen et al., 2016), and archaeological evidence suggests a recent emergence (after 3 ka BP) of camel-based pastoralism in North Africa (Gifford-Gonzales and Hanotte, 2011). The camel was domesticated because of its superb adaptations to harsh conditions, including its superior ability to forage in arid environments and to endure treks across true desert without freshwater. Domestication of dromedaries helped develop extensive caravan routes and maintain trade networks (Gauthier-Pilters and Dagg, 1981). The domestic donkey has been found in contexts across arid zones of Africa and the Arabian Peninsula (Gifford-Gonzales and Hanotte, 2011), but where the process of domestication took place is not completely clear. In any case, the donkey was another animal that was mostly adapted to help humans labor and move goods.

Defining the inception and modality of herding cattle and goat/sheep over North Africa relies on multiple archaeological contexts, but reconstructions remain fragmentary because significant problems exist with the preservation of animal remains, intense erosion of many archaeological sequences, and several methodological biases in site recognition, preservation, excavation methods, and dating (summary in Nicoll, 2001). The vast geographical region is poorly known, and underdocumented. However, evidence from the available records suggests that cattle-based pastoralism spread out from the Levant into NE Africa, the Nile Valley, and the Sahara between ca. 8.3 and 6 ka BP (Fig. 1). The inception of ovicaprine herding seems to be delayed over a few centuries, commencing around 7.8 ka BP (e.g., Smith, 1980; Gautier, 1987; Caneva, 1988; Marshall and Hildebrand, 2002; Smith, 2005; Dunne et al., 2012; di Lernia, 2013a; Wright, 2017, and references therein). With increasing aridification over much of North Africa during the Mid-Holocene, husbandry spread geographically from the Sahel, and pasture grazing intensified (Wright, 2017). The increase in herding inferred for the late Holocene in the Sahel has been correlated with the rising human population (Manning and Timpson, 2014).

Some consider animal domestication and husbandry practices as the most significant cultural innovations during the Holocene period within the African arid and semiarid lands (di Lernia, 2013a; Brass, 2018). Although we are not taking a firm position on when the Anthropocene may have begun, we describe additional contexts associated with the introduction of extensive animal husbandry as part of the definite cultural and economic transition, and we document cultural agency and zoogeomorphological attributes of landscape change preserved in Anthropocene records of North Africa.

4. Zoogeomorphology in arid North Africa

To document the effects of zoogeomorphological processes in arid and semi-arid lands of North Africa, we consider our own observations, collected over decades of fieldwork in the region across the Sahara, Sahel, and the Nile Valley.

As discussed above, desert environments are sensitive and respond quickly to external perturbations. In dryland regions, sensitive landscape units have an intrinsic fragility, which promotes rapid transformation at the onset of specific surface processes. Moreover each component of desert landscape reacts differently to external perturbations. Notably, also the concept of the *Green Sahara* does not refer to a general and widespread of a savanna environment developed over all of North Africa; instead, each landscape element reacted differentially to climate changes, and some areas were not significantly different from today, even during the so-called AHP (Nicoll, 2004; Cremaschi and Zerboni, 2009; Lézine, 2009b). For that reason, each part of the desert landscape may not have preserved evidence of Holocene zoogeomorphological processes. For example, desert pavement that mantles the planar surfaces of sandstone massifs of the Sahara and the alluvial fans along the fronts of mountain ranges has remained considerably stable during the last millennia (Zerboni et al., 2015). This geomorphological unit formed mostly during the Pleistocene, and evidence that zoogeomorphic processes have locally disturbed it in the Holocene exist. The desert pavement is intrinsically fragile and prone to enhanced surface processes when disrupted; this sensitive landscape element is also extremely resilient and able to persist at a new state of equilibrium after disturbance, and it can preserve surface

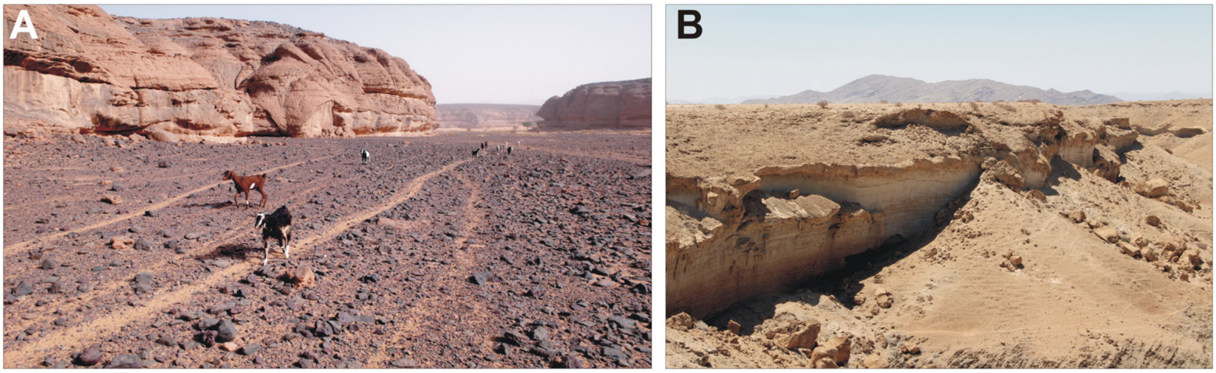

Fig. 3. Trampled trails left by goats on (A) a *hamada* area of the Tadrart Acacus massif (Libya), and, for good comparison, (B) game trails on a fan at the margin of the Namib Desert (Namibia).

changes over millennia. For these reasons, desert pavements and disturbed areas such as tracks and trails in North Africa preserve significant evidence of zoogeomorphological processes that occurred in the Anthropocene.

Although scholars are discussing various opinions about the specific timing of the introduction of domesticated cattle and goats to North Africa (e.g., Gautier, 1987; di Lernia, 2013a; Brass, 2018), the husbandry of cattle and movement of flocks into arid and semiarid regions left direct evidence in semiarid and arid landscapes. Herders started moving their animals across the main North African massifs looking for pasture, and the repeated trampling of cattle and goats created trails along the slopes (Figs. 3, 4). Trampling as well as intense and repeated overgrazing are typical markers for pastoralist activities (see Reynard and Henshilwood, 2018). In the Sahara (Biagetti, 2014) and neighboring

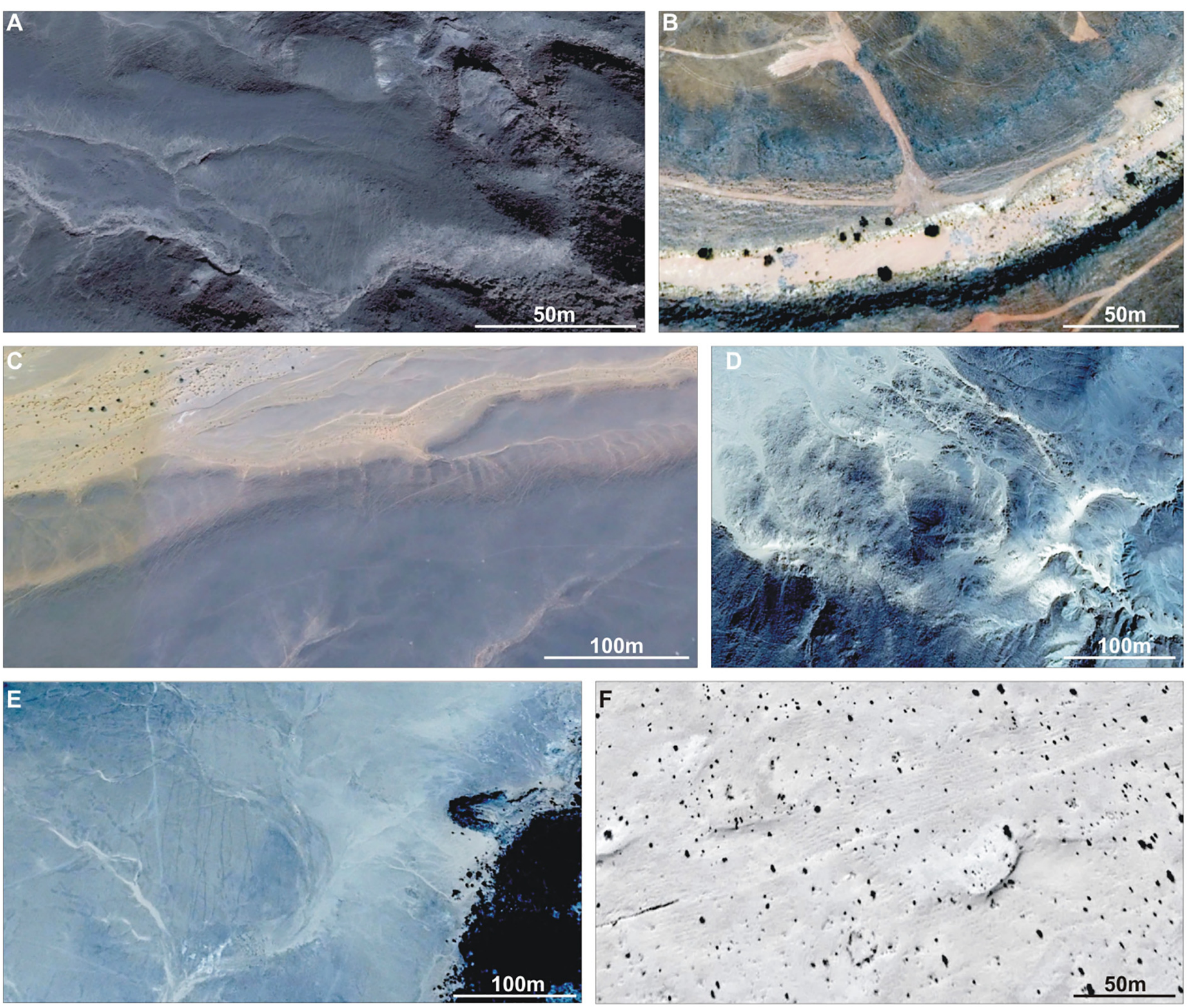

Fig. 4. Trampling trails left by domestic animals in North Africa are evident in Google Earth™ satellite imagery. (A) Northern escarpment of the Messak plateau (Libya). (B) Wadi bank in the central Messak plateau (Libya). (C) Wadi bank in the central Tassili massif (Algeria). (D) Central Aweynat massif (Sudan). (E) Pediment in the eastern Tadrart Acacus massif (Libya). (F) Flat sandy area surrounding Timbuktu (Mali).

deserts, present-day herders occasionally use these trails; the trails are most probably relict, having originated during the introduction of intense herding in the region (di Lernia et al., 2013). We do not have clear evidence about the age when the trails initiated into the desert pavement. However, in many cases laterally displaced pavement stones have a double rock varnish formation: a reddish, Fe-rich coating on the area that was in contact with the soil and a dark Mn-rich rock varnish developed on the subaerially exposed portion of the rock. This occurred because pavement clasts were displaced by animals (i.e., disturbed) before the formation of Mn-rich varnish, which was biomineralized during a phase of increased aridity between 6 and 4 ka BP (Cremaschi, 1996; Zerboni, 2008).

In some places where trails are located in remote regions and are not exploited by modern herders, ancient monuments are present. For instance, Fig. 5 shows some trails in the eastern Tassili massif (Algeria) and along a wadi of the central Messak plateau (Libya). At both these locations, many different prehistoric stone monuments are present, including tumuli, key-hole monuments, and corbeilles (for definition of each type of monuments see: di Lernia and Manzi, 2002; di Lernia, 2006, 2013b). This connection between stone monuments and goat/cattle trails on the *hamada* suggests that trails are part of a very ancient anthropogenic landscape that dates back to the middle to late Holocene transition or earlier.

From a geomorphologic point of view, the development and use of animal trails led to a general zoogeomorphic disturbance on slope processes (sensu Butler et al., 2018), including an increased probability and intensity of debris flows, gully erosion, and surface wash (Butler, 2012) along alluvial fan or escarpments. Evans (1998) suggested that many gullies develop along and/or follow cattle trails in arid and semiarid regions, especially if trails lead to water resources or if they follow the drainage lines. Even trampled trails on flat surfaces have geomorphological effects on surface stability, rendering areas more prone to dust emission and soil loss. If we consider the perspective of high-resolution satellite imagery (Fig. 4), game tracks are often evident; these are single and braided lines (referring to track lines that cross and weave) and distinguishable from vehicle tracks, which are double-parallel, linear and larger. Trails are most evident on the flat *hamada* surfaces or along alluvial fans (Fig. 4); in some cases, trampled trails are also evident on stony pediment surfaces and on thin sand sheets covering thin silty to clayey sediments (Fig. 4).

An unusual example of herding-induced erosion because of trampling has been described on the bare sandstone surface of the Tadrart Acacus massif in SW Libya (Cremaschi et al., 2008). Deeply excavated footprints of cattle or ovicaprine (indeterminate), or footholds, are present along a sandstone slope at the locality named In Ehed (Fig. 6), marking an ancient pathway leading to a rainfed pond that is still active today (di Lernia et al., 2012). The antiquity of the carved trackway is substantiated by the dark, Mn-bearing varnish present within the carved-out, excavated surfaces; the dark varnish is not present on the adjacent noncarved sandstone outcrop exposure. Rock varnish formed on the

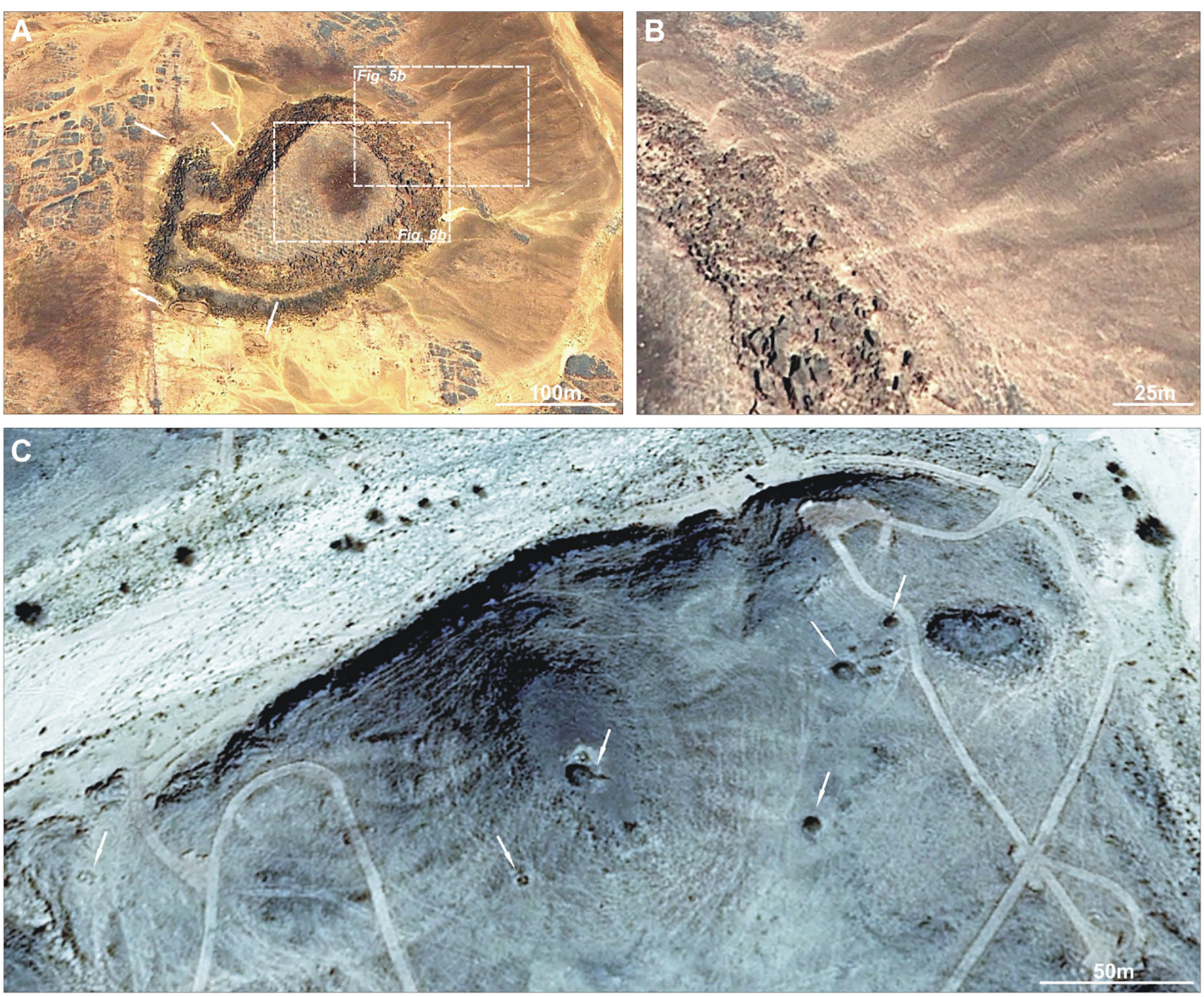

Fig. 5. Snapshots of Saharan archaeological landscapes shaped by humans and domestic animals (Google Earth™ satellite imagery); arrows indicate stone monuments. (A) Stone monuments (key-hole type and tumuli) and trails around a mesa in the eastern Tassili massif (Algeria); the position of Fig. 5B and Fig. 8B is also indicated. (B) A detail of (A) showing trails. (C) Trails and tumuli around a sandstone hill in the central Messak plateau (Libya).

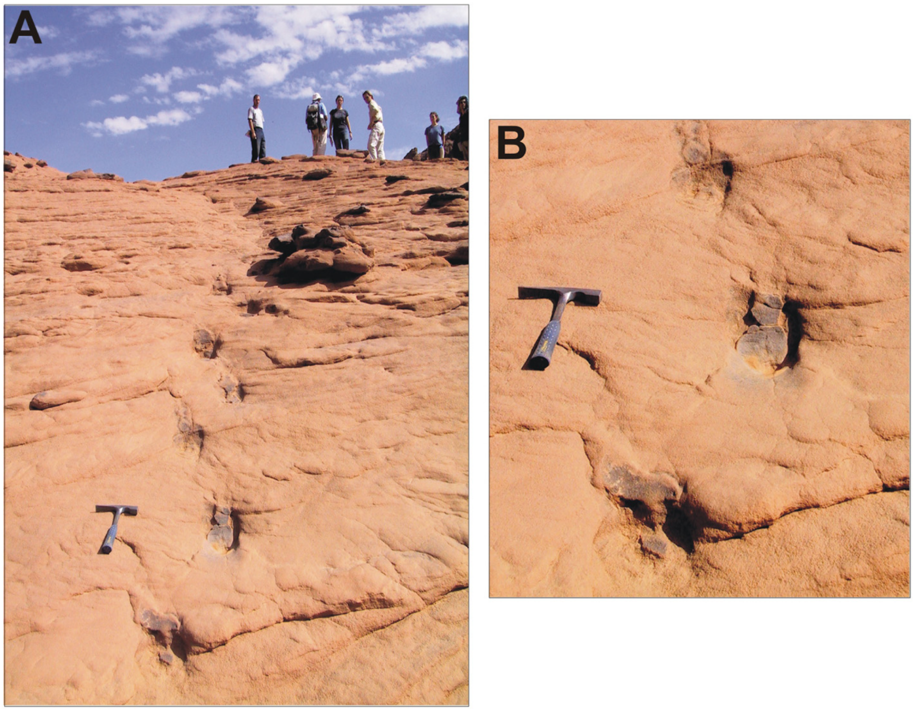

Fig. 6. (A) The steps excavated in Neolithic (?) times by animals along the slopes of the Tadrart Acacus (after Cremaschi et al., 2008); (B) photo detail illustrating the occurrence of rock varnish.

whole rock massif during the mid-Holocene transition to more arid conditions (Zerboni, 2008), but late Holocene wind erosion has removed the varnish, except over the parts of the carved footsteps that were sheltered against deflation.

Some rock shelters and caves preserve additional examples of modifications left by goat herding. Occasionally extensive layers of dung deposited exist within caves and rock shelters (Fig. 7) that were used as stable sites since the late Neolithic in the central Sahara (see di Lernia, 1999; Cremaschi and Zerboni, 2011; Cremaschi et al., 2014) and adjoining regions (e.g., Marinova et al., 2008; Linseele et al., 2010). Even though such practices are limited in extent to specific sites, this animal sheltering process promoted the persistence of humidity within certain rock shelters and supported the biological activity that advanced the biogeochemical degradation of the cave walls (Cremaschi et al., 2008; di Lernia et al., 2016). At Takarkori rock shelter in SW Libya (Cremaschi et al., 2014), for instance, the extensive accumulation of ovicaprine dung during the Early and Middle Holocene and the subsequent formation of efflorescence (niter – KNO_3 – and other solutes) on the rock surfaces of the rock shelter walls undermined the structural stability and caused collapse (di Lernia et al., 2016). Besides biogeochemical weathering of rock surfaces related to microorganisms onsite here (and many others in the region), the dung inside the rock shelter hosted and supported a mesofauna and arthropod community, mostly represented by insects. Among the fauna present are wasps that used the rock surface as a substrate to build up nests, or to excavate the rock leading to its mechanical disruption (Watson and Flood, 1987; Cremaschi et al., 2008; Bednarik, 2014; Orr et al., 2016).

Fig. 7. A rock shelter filled with goat dung in the Tadrart Acacus region.

Zoogeomorphic processes can cause permanent changes to desert landscapes, including armored surfaces and flat *hamada* that are mantled with stone pavement and reg. Desert stone pavements develop over long timescales because of the interplay of deflation removal, aeolian abrasion, and gravity; such surfaces are prone to aeolian erosion after disturbance or dismantling (e.g., Adelsberger and Smith, 2009; Knight and Zerboni, 2018). Besides their vulnerability to trampling and the effects of overgrazing along slopes, flat *hamada* surfaces preserve features caused by animal activities. For instance, dromedaries, domestic goat/sheep and wild game (including the Barbary sheep) excavate daybeds for resting sites (see also Butler, 2012; Butler et al., 2018, for detailed explanation). By trampling in circles at a location or rolling on their back (an activity called a *wallow*), the animals dislocate clasts of the desert pavements, excavating small, subrounded depressions that are free of clasts, and exposing the surface comprised of sandy to silty topsoil to disturbance. These daybed features occur on some flat surfaces that appear dotted with dozens of circles. Daybeds are evident in satellite imagery of the top-flatted interwadi areas of the Tadrart Acacus, Messak plateau, Jebel Awaynat, and Aïr (Fig. 8). Therein, such features can be distinguished from solutional depressions (Perego et al., 2011; Zerboni et al., 2011) because the daybeds are smaller in scale and surrounded by a circle of packed clasts of the *hamada*, which have been emplaced by animal activity.

Dromedary trails, or tracks traversing through the flat areas of desert pavement (*hamada*), are another example of zoogeomorphic disturbance (Fig. 9). Some dromedary tracks are along parts of ancient trans-Saharan trade routes and could potentially date back two

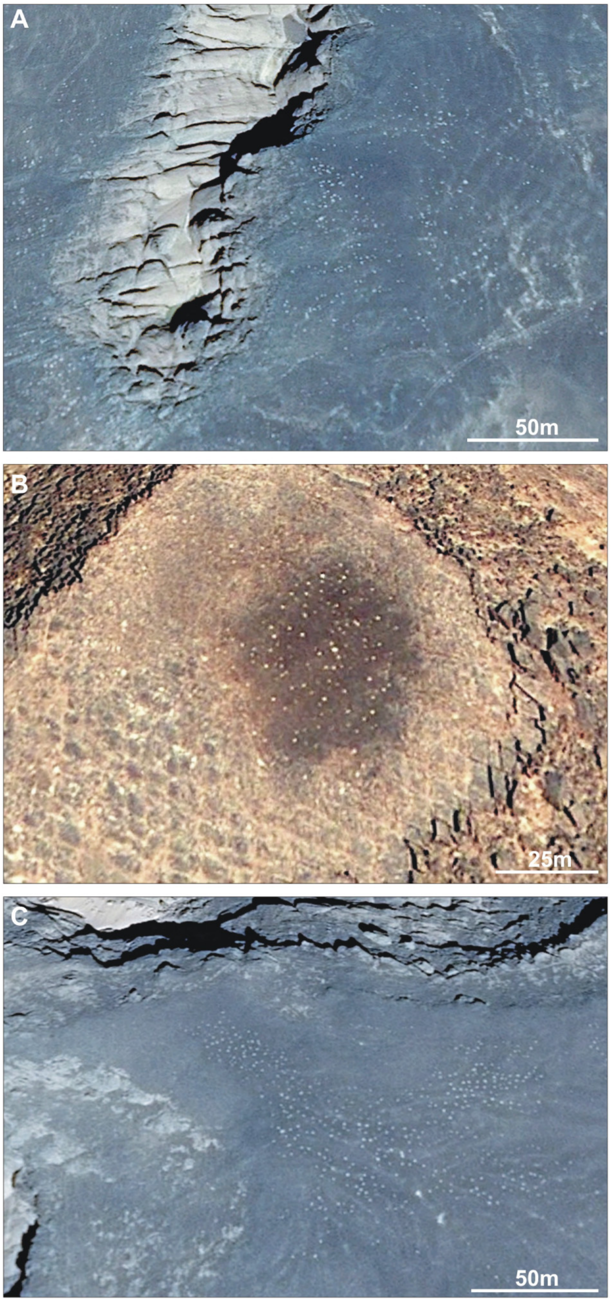

Fig. 8. Excavated circular features are daybeds, the resting sites of dromedaries, domestic goat, and possibly wild goat; these dot the black, flat-topped surface of the Tadrart Acacus (A), Tassili massif (B), and Messak plateau (C) in satellite imagery (Google Earth™).

millennia (Wilson, 2012). The persistent trampling of dromedaries walking along the same path has caused the removal of large clasts and exposure, as well as subsequent compaction of the surface sediments, or topsoil. This is much more evident on disturbed and nonarmoured desert surfaces, where denudation coupled with continued foot-traffic trampling accelerates substrate disturbance and dislodges particles that are removed by aeolian erosion. This has been described as a main effect of camel trampling (Butler, 2018).

5. Dust mobilization in the Anthropocene

Dust mobilization from natural surfaces depends on several factors, including: the intensity of winds; enhanced aridity of the topsoil; the grainsize of surface particles and soil; and the type, quality and extent

Fig. 9. A dromedary trail on the *hamada* of the Messak plateau (trail width ~50 cm).

of land cover and vegetation. Moreover, anthropogenic factors such as land use and overgrazing contribute to increase the dust flux to the atmosphere (Thornes, 2007; Webb and Pierre, 2018). We suggest that some combination of these factors increased the dust emission from North Africa during the mid-Holocene.

5.1. General mechanisms

In the region, animal domestication and husbandry practices reached their apogee during the middle Holocene (di Lernia, 2013a), likely triggering further geomorphic degradation within the sensitive North African environment, which was already experiencing aridification. During this phase, in fact, surface water availability diminished in the Saharan and the Sahelian regions (Gasse, 2000) as the monsoon weakened and rainfall ceased to reach the African continental interior. It is debatable whether the transition toward increased aridity was sudden or gradual (i.e., instantaneous, fast, or slow). Reconstructions of the pace and tempo of aridification vary by geographical location and geomorphic context.

Some geomorphological units in the most continental, remote areas of the Sahara responded rapidly to delimited precipitation events; the springs and lakes between dunes were particularly affected because these are sustained by surficial and shallow aquifers that require meteoric recharge. In contrast, physiographic and freshwater systems connected to large groundwater reservoirs, and those connected to mountain aquifers are less affected by drought and persisted for several hundreds of years. For instance, rivers fed by the Tassili massif aquifer progressively reduce their bedload and length, becoming more and more endorheic toward the late Holocene (Cremaschi and Zerboni, 2009); springs connected to the same hydrological system were active at some localities until a few centuries ago (Cremaschi and Zerboni, 2013).

A slow-rate of general aridification during the middle to late Holocene is suggested also by analyses of a continuous freshwater continental record, a core from Lake Yoa (Chad), which records the long-lasting persistence of a savanna-like vegetation, replacement by desert taxa, and increased dust flux in the late Holocene (Kröpelin et al., 2008; Francus et al., 2013). As stated above, these lines of evidence contrast with the widespread hypothesis of an abrupt interruption of rainfalls over North Africa and the consequent instantaneous aridification of the whole region, which was inferred from ocean core archives of a massive dust input to the Atlantic Ocean at ~ 5 ka BP (deMenocal et al., 2000). This enhanced flux of dust from inland North Africa to the sea was interpreted as *the smoking gun* of a widespread continental-scale aridification and related disappearance of the vegetation cover, as well as the consequent increased wind erosion under arid and

hyperarid environmental conditions. This idea that Saharan and Sahelian landscapes abruptly and rapidly transitioned from humid to arid conditions during the middle Holocene remains the accepted model. However, careful examination of the terrestrial records shows that the timing, space, and magnitude of the transition to arid conditions varied based on geographic gradients (Shanahan et al., 2015).

5.2. A geoarchaeological reinterpretation of dust emission

The concept of an abrupt termination of the AHP was initially interpreted from layers in offshore ocean cores, and has been described as a function of orbitally paced environmental processes and enhanced dust input from the continent. We reinterpret this transition (see Fig. 10) in the broader context of onshore records from North Africa, and we suggest that the enhanced dust flux during the middle Holocene is closely related to processes of human-animal agency that have been overlooked. As geoarchaeologists, we relate the environmental changes observed across the aridifying North African landscape through the lens of a cultural ecological framework (Butzer, 1982), and we suggest that human-animal agency – zoogeomorphic processes – played an important role in amplifying dust generation from the continental interior since ~7 ka BP.

As suggested by Wright (2017), the spatial and chronological discordance of the transitions toward arid conditions underscores the need to identify alternative mechanisms for the progressive denudation of land surfaces and increased dust production over North Africa. The mechanisms related to orbital forcing were primary controls of the existing terrestrial and atmospheric processes during the Holocene (Wright, 2017). We suggest that the adoption and effluorescence of animal husbandry in the Sahara and Sahel contributed to consequent large scale overgrazing and trampling in an aridifying, degrading environment, which directly caused devegetation and landscape denudation, which

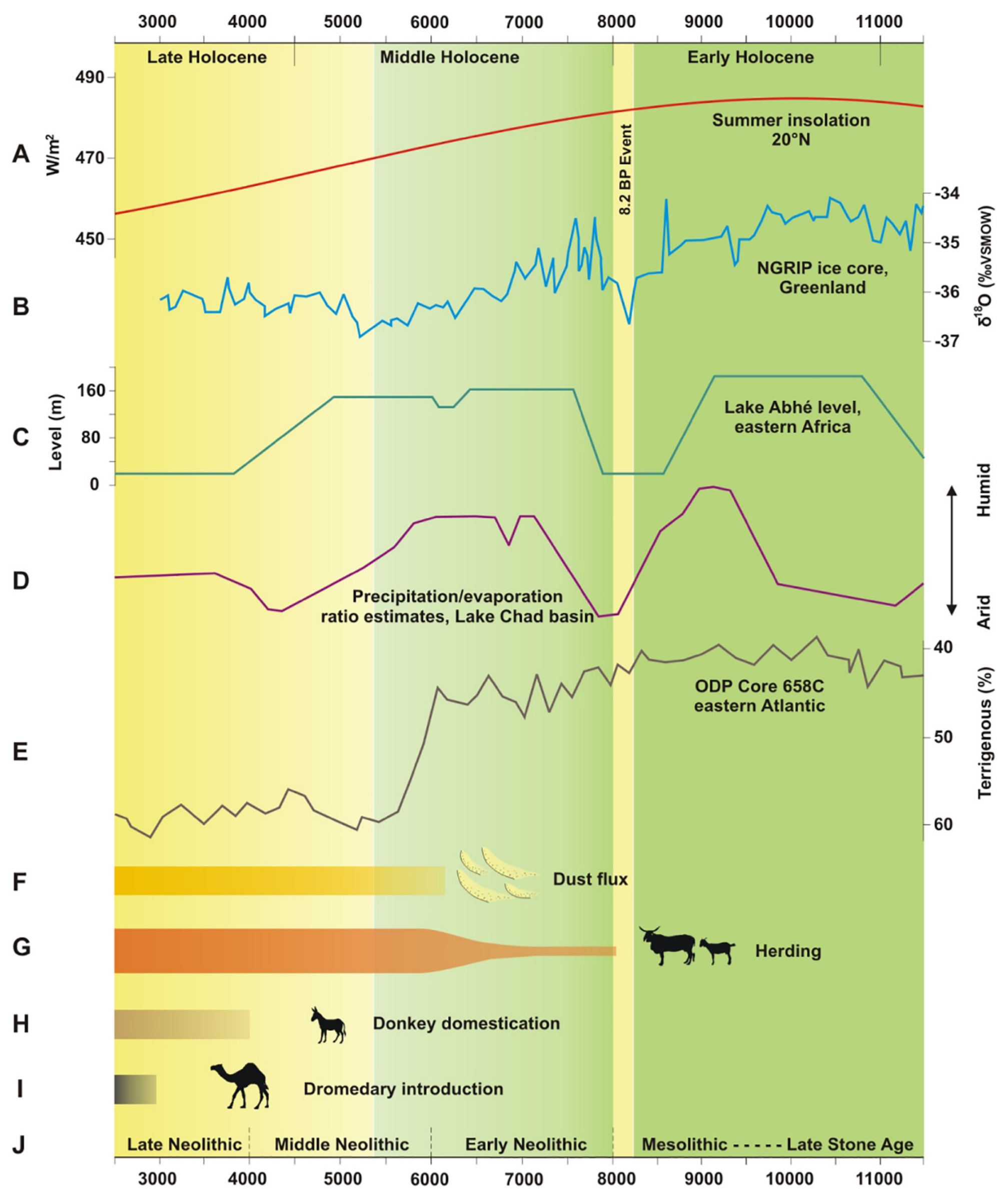

Fig. 10. Diagram illustrating the main climatic changes that occurred in North Africa during the Holocene and the increased dust flux recorded in offshore records when herding was spreading. (A) Mean summer insolation at 20°N (Berger and Loutre, 1991). (B) The $\delta^{18}O$ record of the Greenland NGRIP ice core (North Greenland Ice Core Project Members, 2004). (C) Lake Abhé level changes in eastern Africa (Gasse, 1977). (D) Lake Chad lake-level changes (Servant, 1983). (E) Sahara and Sahel dust record off Mauritania (deMenocal et al., 2000). (F) Inferred increase of dust mobilization. (G) Herding introduction and spreading across North Africa (di Lernia, 2013a, 2013b). (H) Domestication of donkeys (Mitchell, 2018). I) Dromedary introduction in the region (Rowley-Conwey, 1988; Almathen et al., 2016). (J) Main Saharan cultural changes.

enhanced natural desertification within a zoogeomorphically enhanced, positive feedback mechanism. The most evident consequences within these process-response feedbacks included large-scale sediment erosion and soil loss, increased mobilization of fine particles as dust, and enhanced emission of continental dust to ocean basins (Fig. 10).

If we consider North Africa, the efflorescence of animal husbandry within the region roughly corresponds with the timing of the abrupt increase in dust flux to the Atlantic Ocean at the end of the AHP as defined in deMenocal et al. (2000) (Fig. 10). This is evident at the general scale, but Wright (2017) also suggested a site-related correspondence between the introduction of animal domesticates and local devegetation. For instance, records from Ifri Oudadane, Ti-n-a-Hanakaten, and Lake Yoa show a good correspondence between decreased arboreal cover or increased aeolian activity synchronous with the time when pastoralism became the primary subsistence economy (e.g., see Aumassip, 1984; Van Neer, 2002; Kröpelin et al., 2008; Francus et al., 2013; Morales et al., 2013). A similar effect of increased denudation in tandem with the massive spreading of domesticated animal herding practices is recorded in the regional pollen record of the Tadrart Acacus massif (Mercuri, 2008), which indicates a progressive decline of grasses and trees interpreted as a regional response to overgrazing.

Considering archaeological studies relating population and subsistence strategy dynamics (di Lernia, 2013a; Manning and Timpson, 2014; Brass, 2018), we propose that human population growth and activities associated with husbandry created and progressively amplified zoogeomorphological processes that intensified the natural, ongoing desertification of North Africa after the AHP. Overgrazing and animal trampling accelerated erosion, and significantly disturbed the landscape, eroding fine particles from the soil, which amplified the dust emission from continental North Africa and sediment flux to the ocean. Human agency and interrelated zoogeomorphology processes may complement the existing explanation for the unexpected amplitude of the increase in dust that is abruptly recorded in offshore cores (e.g., deMenocal et al., 2000).

The impact of grazing animals can be confused with the effects of climate change, because severe drought in arid lands may provoke the deterioration of the vegetation cover (Graf, 1988; Evans, 1998). Arid and semi-arid range lands, however, may be quite resilient and may recover to their pristine carrying capacity after drought (Warren, 1995), but recovery can only happen when rainfall is sufficient and animals are kept off the range (Evans, 1998). A sizeable literature from several locations and various time periods describes human-enhanced surface processes and soil loss in such cultural range landscapes (Wright, 2017). For instance, several papers described the effects of grazing in the vast prairie grasslands of America by EuroAmerican settlers, which increased pressure on the landscape and caused a shift from grassland to scrubland (to name a few: Jones, 2000; Van Auken, 2000; Grayson, 2011). In many regions of China, the recent practice of raising high population of sheep rapidly has degraded local grasslands by intensifying desertification and sand drifting (Zhaohua, 1982; Ho, 1996). Similarly, in Australia, extensive vegetation change along the valley floors has been attributed to the introduction of grazing animals, rather than climate change, the latter of which has occurred without significantly affecting the vegetation present within the valleys (Prosser, 1996). In the modern Levant, Köchy et al. (2008) recognized a connection between overgrazing and desertification. Another archaeological case of anthropogenic desertification with consequent soil loss and dust mobilization was identified on the basis of many archaeological indicators in the Near East during the Chalcolithic–Early Bronze times (Henry et al., 2017). In this case, desertification occurred during a moist interval across the region; and the analyses of lithic artifacts as well as the occurrence of spherulites and specific phytoliths in sediments related the apparent aridification as the effects of overgrazing by increased goat populations, pushed by socioeconomic factors, including the rise in regional human population, widespread trade and shift to a market economy.

5.3. Is the 8.2 ka BP event in North Africa a smoking gun for anthropogenic/zoogeomorphological overprint in dust mobilization?

The hydroclimatic record of North Africa in the context of global reconstruction further confirms the model of zoogeomorphically enhanced dust mobilization and desertification described here. The early Holocene period of enhanced rainfall over the continent was interrupted by a short-time decrease of precipitation and a period of arid conditions, likely triggered by diminished summer isolation, and the subsequent waning of the African monsoon. This event has been recently informed by several comprehensive continental archives from central, northern, and eastern Sahara. In this hyperarid core of the Sahara, rapid climate change happened slightly before 8 ka BP, possibly linked to the globally evident cold/arid 8.2 ka BP event (Alley et al., 1997; Thomas et al., 2007).

Around 8.2 ka BP, proxy evidence and models indicate an abrupt drainage of ice-dammed lakes in North America, which triggered a significant reduction in Atlantic sea-surface temperature and a strong decrease in evaporation in the Gulf of Guinea offshore Africa (Liu et al., 2003; Wiersma and Renssen, 2006). This diminished the strength of the African monsoon, causing a general reduction in rainfall that is recorded in many archives in the Sahel region. These proxy records indicate freshwater at the Bahr El-Ghazal depression (Servant and Servant-Vildary, 1980) and southward the Sahel at Lake Bosumtwi (Talbot et al., 1984), Lake Abhé (Gasse, 1977), Lake Tanganyika, Lake Malawi (Gasse, 2000), and Lake Tana (Marshall et al., 2011). In the Sahara, evidence of increased aridity during this timeframe was observed at Sebkha Mellala (Gasse et al., 1990), Tin Ouaffadene depression (Gasse, 2000), and I-n-Atei palaeolake (Lécuyer et al., 2016), where the level of ancient groundwater-fed lakes abruptly dropped. Mountain springs and groundwater-fed lakes in the Libyan central Sahara dried out (Cremaschi et al., 2010; Zerboni and Cremaschi, 2012), and a major drop in lake level is registered at Lake Gureinat, in the Sudanese eastern Sahara (Hoelzmann et al., 2010). In the Tadrart Acacus of SW Libya, a reduction of permanent water bodies between 8.3 and 7.9 ka BP is also preserved in a pollen record from anthropogenic sediments (Cremaschi et al., 2014). At the northern margin of the Sahara, Lake Tigalmamine (Lamb et al., 1995) and Lake Sidi Ali in Morocco (Zielhofer et al., 2017) preserve evidence of increased aridity; multiple inland playa lakes in the Egyptian Sahara dried up (Nicoll, 2004, 2012). A change of freshwater discharge from North Africa and the Nile Valley is recorded in a major depositional change of sapropel S1 in the Mediterranean Sea (Ariztegui et al., 2000; Nicoll, 2012; Macklin et al., 2015).

Although proxy records from various locales suggest the occurrence of a rapid and major climate change event ~8.2 ka BP across North Africa, there is no significant increase in dust flux to the oceans at this time (Fig. 10E). This observation may imply that the effects of the 8.2 ka BP event over North Africa were spatially limited; however, the available field evidence from across the whole region suggest an increased aridity in the Sahara and Sahel (Lézine et al., 2011). For these reasons, we infer that the absence of significant North African dust input to oceans around 8.2 ka BP reflects a diminishment or suppression of factors that promote dust mobilization from the ground surface. Because clear evidence of reduced extension or contraction of wetlands and decreased vegetation cover during the 8.2 ka BP event exists, we infer that the absence of continuous domestic animal trampling over disturbed ground surfaces is the limiting factor that explains the diminished dust transport during this timeframe in the early Holocene.

Across the modern arid and semi-arid North Africa, trampling by domesticates over denuded surfaces causes disaggregation of particles; these are a trigger of soil loss, and thus constitutes a main factor in dust production and mobilization (Fig. 11). This was evident during the later arid phase that commenced after ~7 ka BP and intensified around 5 ka BP, when we observe that dust fluxes to the ocean dramatically increased as a function of the spreading of herding practices over

Fig. 11. Cattle and flocks mobilize fine particles contributing to soil loss and dust production today. (A) Goats in a gorge of the Tadrart Acacus massif; (B) cattle in the semiarid Khartoum region of Sudan.

the continent. Finally, it is notable that some researchers (see di Lernia, 2013a) interpreted the regional environmental consequences of the 8.2 ka BP event as a contributing factor of major regional cultural changes in the subsistence strategy. Since the end of the 9th millennium, the transition from a hunter–gatherer culture (Epipalaeolithic/Mesolithic to the early Neolithic phase) at this time corresponds with the introduction of cattle and goat herding as the primary resource across the region (summary: Nicoll, 2012).

6. Conclusions and implications

In this paper, we describe *features* or *elements* in dryland landscapes of Northern Africa that indicate human-animal agency and attest to complex, networked activities over great distances. Because these features (trails, trackways, animal daybeds, stables etc.) have not been readily recognized or documented throughout Sahelian-Saharan North Africa thus far, they are valuable new contexts for reconstructing activities and cultural ecology (sensu Butzer, 1982) during Antiquity. Some of the features are erosional (e.g., game tracks and trails, footholds) and lack chronostratigraphic contexts that we can accurately resolve. Sites like animal dwellings, rock shelters, and game blinds might have potential for further detailed study, particularly if there are stratigraphic contexts associated with characteristic artifacts (e.g., pottery, lithics, metal objects) or dateable materials can be recovered.

The archaeological record attests to the effects of zoogeomorphological processes during the Anthropocene, which have enhanced the rate of ongoing natural surface processes in African drylands and contributed in the shaping of desert landscapes. Intensified zoogeomorphological processes associated with animal husbandry during the Neolithic affected the stability of sensitive landscape units, including the desert pavement and other environments prone to desertification, causing soil erosion by wind deflation that generated dusts and increased offshore dust export to ocean basins, especially after 7 ka BP. During this period in the middle-late Holocene, we suggest that human activities exacerbated environmental changes, and directly contributed to anthropogenic and zoogenic desertification (sensu Henry et al., 2017), especially during periods of population growth, when pastoralism accelerated devegetation.

We reinterpret the increased dust emission from North Africa during the mid-Holocene at the end of the insolation-forced monsoonal maximum AHP. We suggest that the natural trends of aridification were enhanced by human-animal activities that adversely increased denudation, dust production, and broad-scale landscape change (Cremaschi and Zerboni, 2011; Wright, 2017). In North Africa, human activities induced landscape modifications, de-vegetation, and soil loss; these contributed to a reduction of the sequestration of CO_2 in soils and sediments, representing a possible case of early anthropogenic overprints on climate (sensu Ruddiman, 2003).

Today, herding is a widespread practice over North Africa, as much as in the Horn of Africa and in some regions of southern Africa. The available maps of the region representing present-day and ancient land use (e.g., Evans, 1998; Friedl et al., 2002; Terwilliger et al., 2011; Defourny et al., 2014; Kay and Kaplan, 2015) indicate that herding is the most common subsistence practice, associated with opportunistic, occasional, or seasonal agriculture; land use maps generally do not cover the Sahara, which is considered as an empty space that supports some local patches of pastoral landuse. The Sahara and the Sahel are also considered among the largest areas of dust emission on the globe (e.g., Prospero, 1999; Prospero and Lamb, 2003; Engelstaedter et al., 2006; Gherboudj et al., 2017); this is because of its dominant arid to hyperarid climatic conditions and extremely limited vegetative cover. But land overgrazing and intensive pastoralism contribute to soil loss and dust mobilization over the region.

Satellite observations, including interpretations from MODIS and the recently acquired SEVERI with fine temporal resolution, allow identification of specific North African dust sources in the contemporary Sahel (Schepanski et al., 2007; Washington et al., 2009; Crouvi et al., 2012). The major plumes contributing dust (called hotspots) have been traced over central Sudan and the central-western Sahel during the modern day (Engelstaedter et al., 2006; Schepanski et al., 2007; Bou Karam et al., 2008; Ginoux et al., 2012; Evan et al., 2015). One important dust emission spot is located in the region westward of the Khartoum-Omdurman conurbation, where the largest domestic animal market of Sudan is located; today, domestic stocks gather therein from the largest breeding areas of the country located in the Darfur and Kordufan regions (Fig. 11). In the central-western Sahel, dust emission occurs across a wide region along the main rivers where pastoral land use is systematically widespread today.

To recap, the Sahel region has long remained naturally drought-prone, with abrupt and severe changes in surface water dynamics, today and in the past; its landscape is extremely sensitive to actions of people and animals that are grazing, herding, and migrating. Moreover, many of the regions that are drought-prone and are experiencing natural desertification today (for instance, the Sahel and the Horn of Africa) are areas where herding is the main subsistence strategy for millions of people (Liao, 2018). Herding affects the local environment, often pushing its resilience beyond sustainability limits (Whiteford, 2002; Reynolds et al., 2003; Geist and Lambin, 2004).

Resolving the role of human and animal agency in geomorphic systems and defining thresholds of environmental change can inform better management approaches to avoid or mitigate the degradation of the African drylands. As these regions face population pressures and hydroclimate changes, responsible use of natural resources and sustainable grazing on fragile ecological and geomorphic niches is essential to avoid an anthropogenic acceleration toward the tipping point for the onset of irreversible soil loss and landscape degradation (Liao, 2018).

To achieve sustainability, more detailed land use maps at suitable scales across the whole of Africa are required to understand and eventually prevent or mitigate overgrazing (Thornes, 2007). Interdisciplinary insights can inform sustainable practices to reduce landscape instability, soil loss, and dust mobilization, and to delimit feedback mechanisms that are anthropogenic.

Furthermore, forward-looking scenarios forecast increasing natural desertification over North and East Africa (e.g., Thomas and Nigam, 2018). It is essential to reduce further anthropogenic contribution to dust mobilization and soil loss, and to consider how humans might deccelerate geomorphic stability and the inevitable environmental degradation. Defining sustainable animal husbandry practices is paramount — understanding the past practices and paleogeographies of our ancient ancestors provides crucial contexts for resilience planning in the present day. Knowledge of the past can hopefully inform strategic solution innovations that could help prevent social crises in the face of famine and mass migrations.

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